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Investigating wind turbine dynamic transient loads using contactless shaft torque measurements

Donatella Zappalá¹ ✉, Christopher J. Crabtree¹, Simon Hogg¹

¹Department of Engineering, Durham University, Durham, UK

✉ E-mail: donatella.zappala@durham.ac.uk

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Abstract: The wind industry is showing increasing awareness about the importance of long-term direct shaft mechanical torque measurements to fully understand wind turbine (WT) dynamics, adopt proactive solutions for extreme load mitigation and enhance condition monitoring (CM) capabilities. Although torsional effects are important, torque measurement on such large, inaccessible machines is practically and logistically difficult, mainly because of the costly and intrusive specialised equipment currently available. This study details an experimental set-up for the investigation of shaft dynamic transient load and speed measurements through a contactless, low-cost torque meter. Results are obtained over a range of applied loads and compared with reference measurements from an in-line, invasive torque transducer. Average torque and speed root-mean-square error values of 0.53 Nm and 0.35 rpm, respectively, indicate good accuracy of the proposed contactless torque meter. Its implementation in the field would allow direct, cheap, real-time measurements of WT drive train loads for performance monitoring, control and CM purposes.

1 Introduction

As large-scale wind farms move further offshore, it is essential to keep a competitive cost of energy by achieving a high availability and capacity factor, and ensuring that loss of energy and wind turbine (WT) downtime are minimised. Offshore wind operations and maintenance (O&M) incur costs up to 25% of the total levelised cost of energy [1]. Unscheduled maintenance activity has been shown to account up to around 65% of O&M costs [2], resulting in unexpected WT downtime, reduced availability and lost revenue. Repair costs are not the only consequence of maintenance, as the WT downtime and revenue costs must also be considered. These issues highlight the importance of O&M strategy within economic viability evaluation of large offshore wind farms. The adoption of cost-effective condition monitoring (CM) techniques is crucial in reducing O&M costs, avoiding catastrophic failures and minimising costly unscheduled maintenance. As the loading on the WT drive train components is highly variable, the study of transient conditions is fundamental to the development of reliable CM techniques.

WTs experience a broader range of dynamic loads than most other large conventional rotating machines. Load variations originate from the grid/generator due, for example, to curtailments, grid loss, voltage changes, emergency stops, shutdowns etc., as well as from very frequent and occasionally extreme wind changes such as gusts, storms and sudden wind losses. Transient events, occurring during control actions or anomalous wind speed behaviour, can cause highly variable drivetrain loads. These can lead to unexpected torque reversals [3] that can be harmful to WT drive train components and reduce their expected life [4].

During extreme transient conditions, dynamic torsional loading causes rapid unloading/loading up of the drive train and loading up/unloading in the opposite direction. These occur in fractions of seconds, unlike the typical minute timescale captured by supervisory control and data acquisition (SCADA) systems. This creates oscillations affecting the entire turbine drive train system. Premature failures of some gearbox components have been associated with overloading experienced by the drive train [5]. Direct high-frequency real-time measurements of drive train loads can improve confidence in drive train design and allow the adoption of proactive solutions for extreme load mitigation.

Mechanical torque measurements are also relevant for efficient CM during turbine operational life, and for condition-based

diagnosis for reliable and safe operation [6]. The potential of monitoring different WT drive train components using direct measurements of the shaft mechanical torque signal is significant, as it contains information on the mechanical response to wind before any generator effects. Recent studies have shown the potential benefits of adopting CM systems (CMSs) based on the measurement of WT shaft torque for the detection of rotor electrical asymmetry and machine winding faults [7–9], mass imbalance [10], gearbox failures [11], blade mass imbalance and aerodynamic asymmetry [12].

Owing to the costly and intrusive nature of measurement equipment [13], which is impractical for long-term use on operating WTs, there is currently a lack of insight into dynamic WT drivetrain behaviour. Furthermore, torque sensors are not currently used in commercial WT CMSs. This paper presents the experimental investigation of a novel contactless, low-cost torque meter for shaft load and speed measurements, with a focus on tracking transient conditions for use in a CMS. The adoption of the proposed technique would allow mechanical torque and speed measurement, and monitoring across the machine operational life. It relies on the instrumenting of its shaft with a set of two barcodes and optical probes, one at each end of the shaft, as outlined in the next section.

2 Contactless shaft torque measurement

The contactless torque meter proposed in this research consists of two black and white striped codes, with equal stripe pairs, directly glued around the shaft scanned by two optical sensors mounted on non-rotating supports. The operating principle of the contactless torque meter has been described in details in [14]. As schematically shown in Fig. 1, when a torque is applied to the rotating shaft, it produces a relative shaft twist, θ , resulting in a time shift, Δt , between the pulse trains generated by the optical probes. The measurements of Δt and of the pulse train period, τ , allow the calculation of the shaft absolute twist angle, θ_a , and rotational speed, n , as [15]

$$\theta_a = \frac{2\pi}{60} n \Delta t \quad (1)$$

$$n = \frac{60}{\tau \text{ppr}} \quad (2)$$

where ppr is the number of pulses per shaft revolution. Owing to mounting misalignment between the two optical probes and/or the two zebra tapes, the shaft absolute twist angle, θ_a , could differ from the shaft relative twist angle, θ , which is calculated as

$$\theta = \theta_a - \theta_{a,0} \quad (3)$$

where $\theta_{a,0}$ is the shaft apparent angular shift at no-load conditions.

Shaft torque measurement can then be indirectly obtained from the known system calibration curve, that is, the relationship between the shaft relative twist angle, θ , and torque, T , for a given shaft and material, described by [16]

$$T = I\ddot{\theta} + C\dot{\theta} + K\theta \quad (4)$$

where I is the rotating system moment of inertia, C is the shaft damping coefficient and K is the shaft torsional stiffness.

3 Experimental set-up

The contactless torque meter has been tested on the experimental test bench shown in Fig. 2. The rig features a 4-pole 5 kW grid-connected induction generator (IG) driven by a 4-pole 5 kW induction motor (IM). The shaft speed profile is controlled by an ABB drive. A variable transformer connected to the IG allows variation of the stator voltage and hence of the torque acting along the shaft. The IG stator voltage can be varied up to a precautionary safety limit of its armature winding current of 8 A, allowing a maximum torque achievable during operation of 16 Nm. The main shaft is instrumented at each end with a barcode featuring eight equal black–white segments, with a 5.5 mm stripe width, fitting exactly around the shaft. The barcode stripe pair number was selected as a trade-off between measurement uncertainty and computational cost. In correspondence to each bar code, an Optek reflective line reader sensor is mounted on a stationary rigid support, placed at the optimum distance of 0.76 mm from the target. The distance between the two optical sensors is 45.8 cm. An in-line Magtrol TMB 313/431 torque transducer is mounted on the test bench and, being a well-established state-of-the-art technique,

it has been assumed as the reference measurement system during the experimental campaign. The in-line transducer is also used as a reference tachometer as it outputs 60 ppr for speed measurements. Signals from the optical probes and the reference torque transducer are acquired by a PicoScope 4824 oscilloscope, with a sampling frequency, f_s , of 100 kHz.

4 Data processing

A LabVIEW programme (VI) has been implemented to automatically process the optical probe pulse signals and obtain the shaft angular shift by direct timing of their rising edges.

The main steps of the optical system data processing are:

- (1) signals are first initialised to overcome any problems associated with initial probe and barcode mounting offset;
- (2) the time at which the rising edges of the two initialised signals occur is captured by applying an edge trigger with a threshold level equal to half the peak-to-peak signal amplitude;
- (3) a flicker filter is applied to remove any possible timing errors from signal flickering around the trigger level;
- (4) the shaft rotational speed, n , is calculated from the pulse train period by applying conventional rotary encoder techniques, as detailed by (2);
- (5) an eight-point moving average filter, with seven-point overlap over time, is implemented to calculate the pulse time shift. This is to reduce inherent periodic noise in pulse timing due to tangential and radial displacements between the shaft and optical probes, typically caused by vibrations or shaft deformation; and
- (6) the shaft absolute angular shift is then calculated according to (1).

Table 1 summarises the main features of the contactless torque meter mounted on the test bench.

5 System calibration

The contactless torque meter calibration curve has been obtained by comparison with the reference measurements of the in-line torque transducer. The calibration process is schematically shown in Fig. 3. Steady-state tests were performed on the test rig at four different shaft speeds. For each case, no-load and different torque

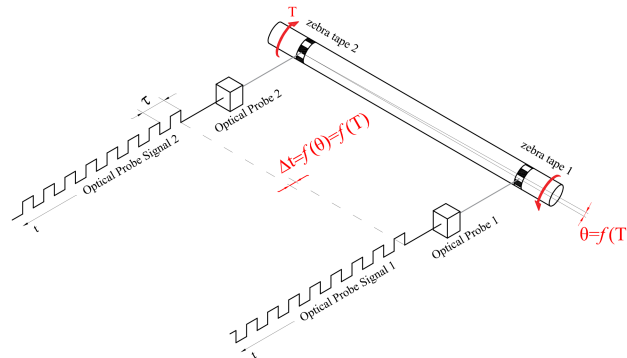


Fig. 1 Operating principle of the contactless torque meter [14]

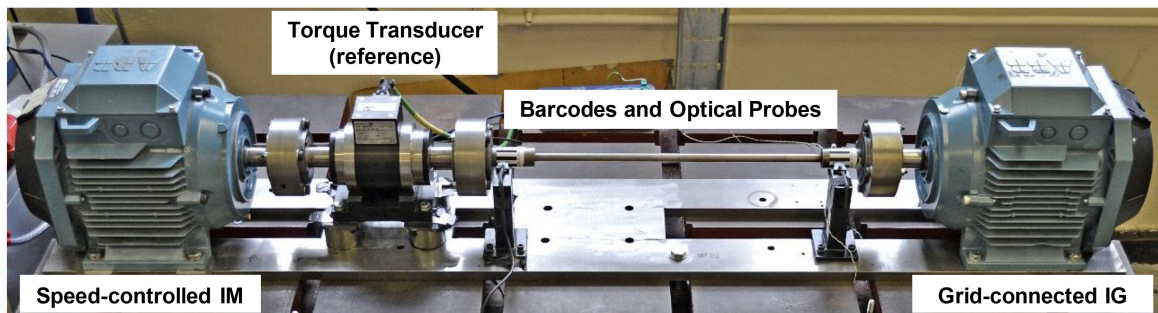
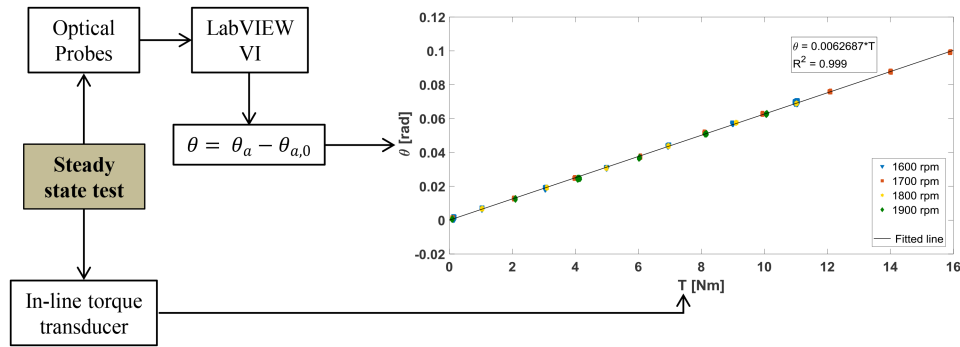


Fig. 2 Experimental test rig

Table 1 Main parameters of the experimental optical torque meter

pulses per revolution (ppr)	8
barcode period	11 mm
measurable angular range	$\left[-\frac{\pi}{\text{ppr}}, \frac{\pi}{\text{ppr}}\right]$
angular resolution ($\delta\theta$)	$\frac{2\pi n}{60f_s}$
angular twist sampling frequency	$\frac{n \text{ ppr}}{60}$

**Fig. 3** Schematic representation of the calibration process**Table 2** Summary of the experimental work performed on the torque test rig

Test	Torque range, Nm	Speed range, rpm	Test duration, s	WT operation	RMSE	
					Torque, Nm	Speed, rpm
turbulent torque oscillations (Fig. 4)	-0.8 to 17	1671 to 1706	30	normal running, turbulent conditions	0.53	0.31
drastic shaft torque increase (Fig. 5)	-1.2 to 7.3	1681 to 1702	5	starting event	0.48	0.35
drastic shaft torque reduction (Fig. 6)	-2 to 13.2	1704 to 1756	5	stopping event	0.53	0.45
variable frequency torque fluctuation (Fig. 7)	4.3 to 10.2	1686 to 1697	28	rapid torque fluctuations	0.54	0.31
variable shaft speed (Fig. 8)	2.9 to 13	1547 to 1853	9	variable speed	0.59	0.33

levels, up to 16 Nm, were applied for around 10 s and corresponding signals were recorded and processed.

The linear regression between the shaft relative twist and the corresponding reference torque, measured by the in-line transducer, has provided the system calibration curve. As predicted by (4), the torque-twist trend is linear under steady-state conditions. The calibration curve shows an R^2 value of 0.999, indicating a good fit of the experimental data by the regression line. The statistical analysis of the residuals of the calibration data has provided an expanded measurement uncertainty, with respect to the system full-scale torque, of $\pm 0.3\%$ [14].

6 Results

Experiments have been performed to emulate shaft dynamic transient loads experienced by a WT drive train, during anomalous wind speed fluctuations and control actions. Table 2 shows the details of each experiment including the torque and speed range the duration and the WT operating condition emulated on the test bench. In each case, the contactless torque meter torque and speed measurements, and dynamic response have been compared with those of the reference in-line torque transducer. The performance of the contactless torque meter against the reference system has been estimated by calculating the signal root-mean-square error (RMSE), as detailed in Table 2. Both signals have been resampled at the same frequency of 200 Hz to allow RMSE calculation.

Results shown in Figs. 4–7 have been obtained by varying the IG stator voltage through the variable transformer. The corresponding changes in speed are the result of the applied torque that was not countered by the variable speed drive connected to the IM. Fig. 4 shows results for the case of turbulent torque

oscillations, similarly to those encountered in WT normal running under turbulent conditions. Both the contactless metre torque and speed measurements allow tracking the turbulent shaft oscillations, during the whole transient without any time delay. Figs. 5 and 6 show the effects of torque reversal due to a drastic increase and reduction of the shaft torque, as typically occurring in WT starting and stopping events, respectively. In both cases, the torque meter measurements show good agreement with reference measurements.

Fig. 7 shows the good performance of the optical torque meter during torque harmonic fluctuations, with frequency varying between 0.28 and 0.76 Hz, imposed on the shaft. Results shown in Fig. 8 have been obtained by applying rapid and significant variations to the shaft speed via the ABB drive at a fixed generator stator voltage. The optical measurements, though giving, in the case of the torque, a slightly higher RMSE value than in previous experiments, correlate closely with the reference measurements, showing a good dynamic response to shaft speed and load changes.

The RMSE values of the performed tests, shown in Table 2, are consistent and indicate good accuracy of the proposed contactless torque meter, with the closeness of agreement between its measurements and the reference torque and speed values measured by the in-line torque transducer. Overall, the investigated shaft transient load conditions show average RMSE values of 0.53 Nm and 0.35 rpm for the torque and speed, respectively, corresponding to 3.3 and 0.02% of the maximum operating conditions tested during the experiments.

7 Discussion

Long-term mechanical torque measurements are important for fully understanding the WT dynamics and for CM purposes. In the wind

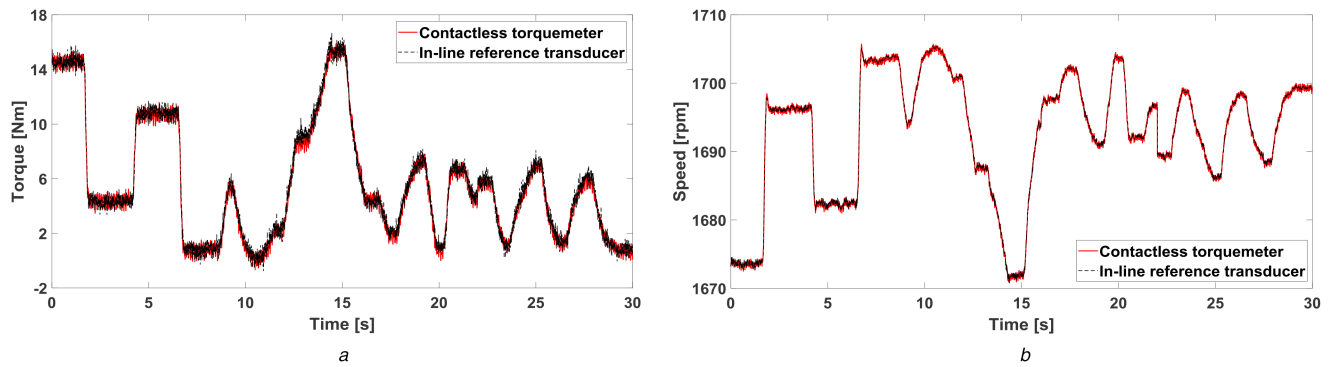


Fig. 4 *Turbulent torque oscillations*
(a) Torque, (b) Speed measurements

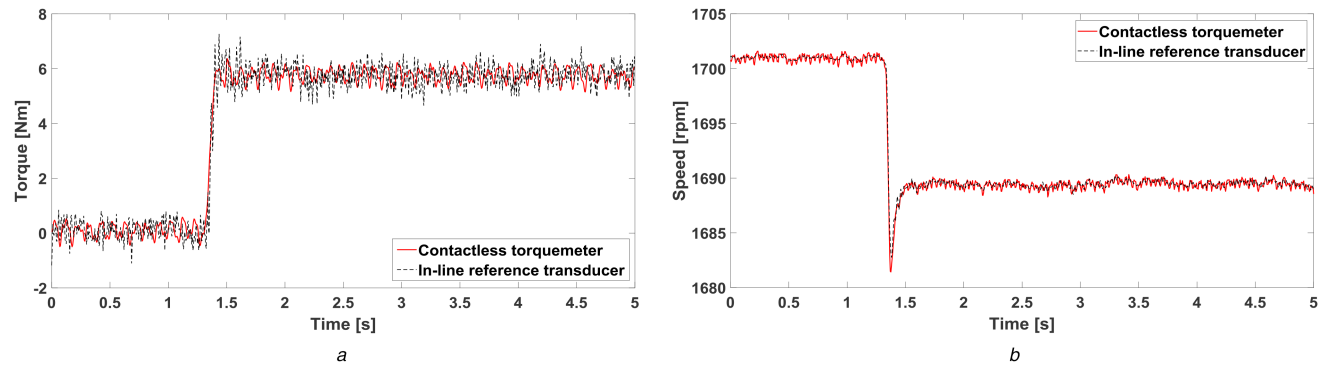


Fig. 5 *Drastic shaft torque increase*
(a) Torque, (b) Speed measurements

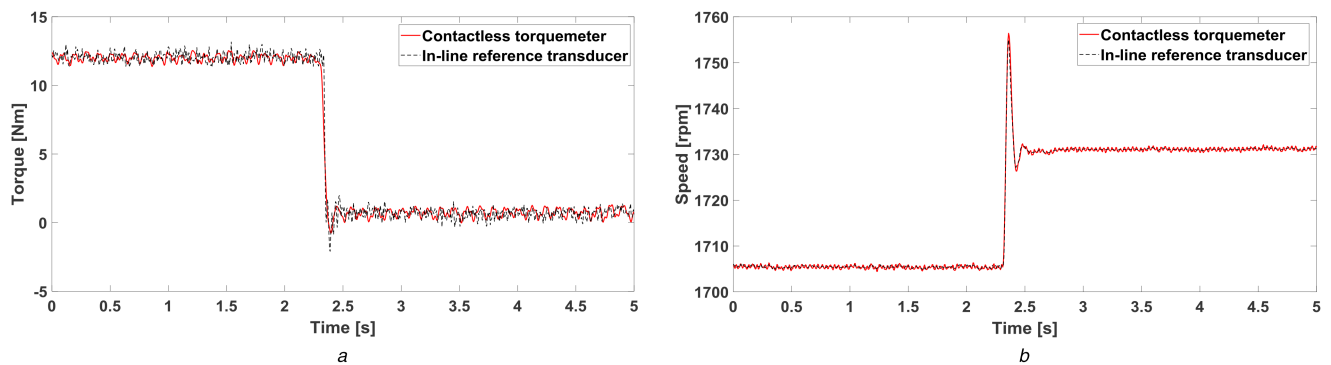


Fig. 6 *Drastic shaft torque reduction*
(a) Torque, (b) Speed measurements

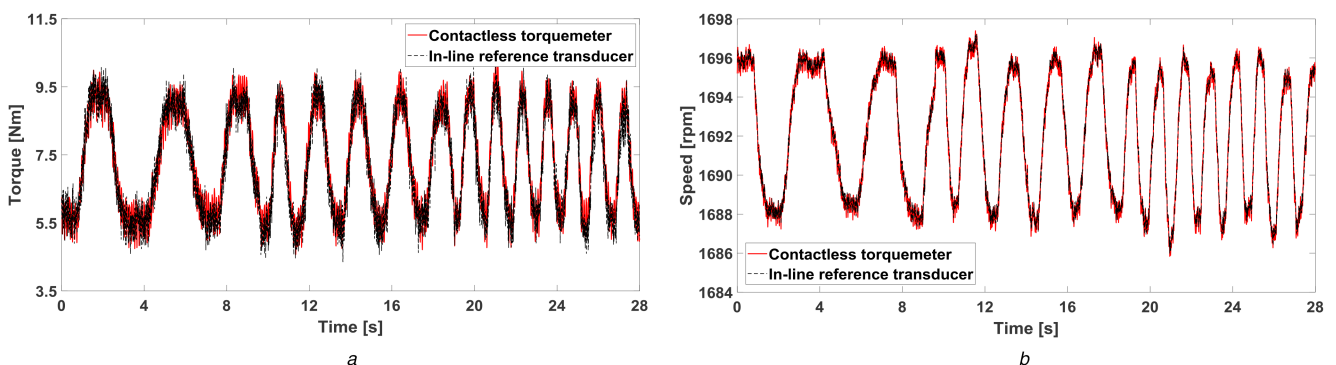


Fig. 7 *Variable frequency torque fluctuations*
(a) Torque, (b) Speed measurements

industry, there is increasing awareness and growing interest in measuring the machine loads by direct, cheap and non-intrusive techniques.

In this work, the use of a contactless torque meter to measure WT drive train shaft torque and speed is experimentally

investigated. Unlike conventional in-line torque transducers and conventional strain gauge techniques, this torque meter does not require costly embedded sensors, electronics or wires on the rotating shaft. It is relatively simple and cheap to implement into a commercial WT CMSs for non-intrusive torque monitoring. Also,

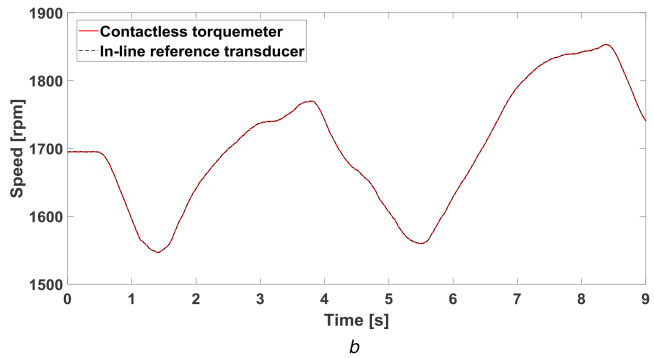
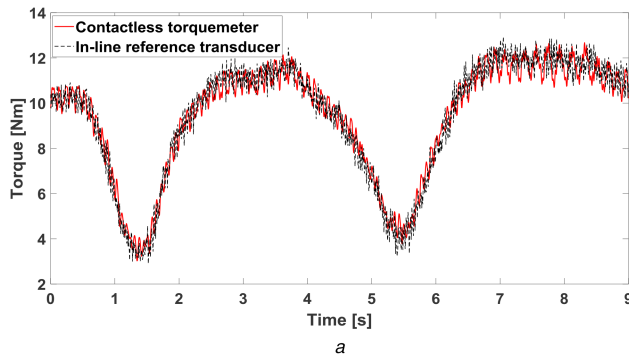


Fig. 8 Variable shaft speed
(a) Torque, (b) Speed measurements

the accuracies of strain gauges often do not meet engineering requirements due to crosstalk phenomena, which can significantly increase the measurement uncertainty [17]. The proposed system allows direct measurement of the shaft dynamic behaviour at relatively high frequency, under transient conditions that have been shown to be the most critical for the WT drive train components. Such a measurement is more advantageous compared with deriving the electromagnetic torque from the measure of the machine electrical power, which does not provide direct and realistic information about the WT drive train dynamics, due to internal frictional, electric and magnetic losses affecting the measurements.

Although still at the small-scale stage implementation, the economic benefits of the proposed technique over conventional in-line torque transducers are evident. The contactless torque meter installed on the experimental test bench costs overall €100. It compares well with the cost of the corresponding reference in-line sensor, which goes well beyond €5000. The difference in costs will be, of course, even larger in a commercial WT application, due to the much larger shaft sizes.

8 Conclusions

This paper presents a novel, contactless torque meter for direct real-time measurement of WT drive train load and speed. The performance and accuracy of the proposed optical torque system during dynamic transient load conditions have been experimentally demonstrated through comparison with reference measurements from an in-line torque transducer. Results indicate good accuracy of the proposed contactless torque meter, with average RMSE values of 0.53 Nm and 0.35 rpm for the torque and speed, respectively. Unlike conventional measurement methods, the proposed barcode torque meter does not require costly embedded sensors or shaft-mounted electronics. It can also be designed to be fitted, or retrofitted, on any WT shaft diameter and material without mechanical interference. This overcomes the majority of problems currently limiting the industrial direct real-time measurements of WT drive train loads for performance monitoring, control and CM purposes.

9 Acknowledgment

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